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Estimating Free-flow Speed from Posted Speed Limit Signs

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Abstract

In 2010 Highway Capacity Manual, one preferably determines free-flow speed (FFS) by deriving it from a speed study involving the existing facility or on a comparable facility if the facility is in the planning stage. Many have used a 'rule of thumb' by adding 5 mi/h (10 km/h) above the posted limit to obtain FFS without justification.

Two team members using a radar gun and manual tally sheets collected 1668 speed observations at ten sites during several weeks. Each site had a unique posted speed limit sign ranging from 20 mi/h (30 km/h) to 75 mi/h (120 km/h). Five sites were on urban streets. Three sites were on multilane highways, and two on freeways.

Goodness-of-fit test results revealed that a Gaussian distribution generally fit the speed distributions at each site at a 5% level of significance. The best-fit model had a correlation coefficient of +0.99. The posted speed limit variable was significant at 5% level of significance. Examining data by highway type revealed that average free-flow speeds are strongly associated with posted speed limits with correlation coefficients of +0.99, +1.00, and +1.00 for urban streets, multilane highways, and freeways, respectively.

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keywords: free-flow speed; posted speed limit; model; speed limit sign; highway;

1. Introduction

1.1. Posted speed limit

Policy makers ultimately set posted speed limits (Parma, 2001). According to the Manual of Uniform Traffic Control Devices (MUTCD), "The Speed Limit (R2-1) sign (see Figure 2B-3) shall display the limit established by law, ordinance, regulation, or as adopted by the authorized agency based on the engineering study (MUTCD, 2010a)." However, professionals have formulated many models such as USLimits (USLimits, 2010) and guidelines

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to aid policy makers in determining a posted speed limit. Policy makers usually consider such factors as land use along the adjacent highway, crash rates, number of driveways, number of intersections, zoning, parking presence, section length, design speed, and highway function as a guide for determining posted speed limits. For instance, one does not post a six-lane, divided, highway with full control of access at 30 mi/h (50 km/h). One does not post an urban street with on-street parking at 75 mi/h (120 km/h). Further, the MUTCD states, "The speed limits displayed shall be in multiples of 5 mph (MUTCD, 2010a)." Previous research mentions that posted speed limits significantly influence traffic speeds (Ottensen and Krammes, 2000), (Rowan, 1959).

1.2. Free-flow speed

The definition of free-flow speed (FFS) from the 2010 Highway Capacity Manual (HCM) is: "1. The theoretical speed when density and flow rate on a study segment are both zero. 2. The prevailing speed on freeways at flow rates between 0 and 1,000 passenger cars per hour per lane (pc/h/ln) (HCM, 2010a)." In summary, speeds of drivers travelling as desired given prevailing conditions such that no preceding vehicle influences the drivers' speeds serve as the basis for space mean speed. Thus, traffic flow needs to be low when one derives mean FFS of drivers from field observations. Examples of prevailing conditions that affect a driver's speed are lane width, weather, horizontal alignment, vertical alignment, sight distance, lateral clearance, design speed, behavior, and adjacent environment (Garber and Gadiraju, 1989), (Oppenlander, 1966), (Ottensen and Krammes, 2000), (Rowan and Keese, 1962).

1.3. Dependent relationship

The relationship between mean FFS and posted speed limit is partially dependent on each other. The FFS partially depends upon the posted speed limit because many drivers comply with posted speed limits else they risk receiving a traffic citation from a police officer or in the mail. The posted speed limit is partially dependent upon FFS in that the MUTCD states, "When a speed limit within a speed zone is posted, it should be within 5 mph of the 85th percentile speed of free-flowing traffic (MUTCD, 2010b)." Engineers should derive free-flow speeds along midblock or pipe segments outside the influence of intersections, merge, diverge, and weave areas. The MUTCD states, "Speed studies for signalized intersection approaches should be taken outside the influence area of the traffic control signal, which is generally considered to be approximately 1/2 mile, to avoid obtaining skewed results for the 85th percentile speed (MUTCD, 2010b)."

2. Methodology

2.1. Design of experiment

To determine the relationship between mean FFS as the dependent variable and posted speed limit as the independent variable, one formulates a design of experiment. To capture a wide range of posted speed limits, the selection of ten midblock and pipe segment sites occurred. Each site had a different posted speed limit. The maximum posted speed limits of the sites ranged from 20 mi/h (30 km/h) to 75 mi/h (120 km/h), specifically 20 mi/h (30 km/h), 25 mi/h (40 km/h), 30 mi/h (50 km/h), 35 mi/h (55 km/h), 40 mi/h (65 km/h), 45 mi/h (70 km/h), 50 mi/h (80 km/h), 60 mi/h (95 km/h), 65 mi/h (105 km/h), and 75 mi/h (120 km/h) sites. To capture FFS variations, the team observed nine sites on three different weekdays and one site on four different weekdays. For all dates during daylight off-peak periods, driver visibility was clear and the pavement surface was dry. To ensure free-flow conditions, all speed observations were made at flow rates less than 500 veh/h and average headways more than 7.0 seconds as shown in [Table 1](#) (Currin, 2001), (Homburger, 1996), (Robertson, 1994). At all sites and using a radar gun, the team measured instantaneous speeds within an approximately 50-ft (15m) midblock or mid-pipe segment length.

The study team measured instantaneous speeds of passenger cars with a strategically placed Doppler device commonly known as a radar gun (Kustom Signals, Inc., 2007). During the same time of speed observations, a team member manually tallied and counted traffic entities to ensure that speed observations occurred at low flow rates. Two team members were necessary to measure speeds and tally traffic at each site.

2.3. Sample size

Observations of instantaneous speeds occurred at each site until speeds of 100 passenger cars (pc) or more were observed as stated in HCM 2010 (HCM, 2010b). Table 1 shows the number of instantaneous speed observations and corresponding flow rates by site. The team made 1668 instantaneous speed observations for the entire study.

Table 1: Data Summary

Site No.	Facility Type	Collection Dates in 2010	Duration, minutes	Posted Spd. Limit, mi/h	Spd. (Non-Spd.) observations	Flow Rate, veh/h	Headway, seconds
1	Urban St	19, 24 Feb; 3 Mar	20; 13; 13	20	175 (64)	313	11.5
2	Urban St	22, 26 Feb; 1 Mar	25; 20; 22	25	153 (21)	161	22.4
3	Urban St	19, 24 Feb; 3 Mar	13; 10; 13	30	165 (33)	333	10.8
4	Urban St.	15, 19, 24 Feb; 15 Mar	20; 15; 16; 10	35	213 (68)	283	12.7
5	Urban St	15, 24 Feb; 3 Mar	16; 10; 9	40	170 (98)	461	7.8
6	Mutilane Hwy	22, 26 Feb; 1 Mar	12; 13; 12	45	162 (36)	322	11.2
7	Mutilane Hwy	15, 24 Feb; 17 Mar	30; 17; 18	50	158 (64)	206	17.5
8	Mutilane Hwy	22, 26 Feb; 15 Mar	23; 25; 21	60	154 (7)	141	25.5
9	Freeway	15, 24 Feb; 15 Mar	25; 8; 10	65	155 (11)	296	12.2
10	Freeway	3, 15, 17 Mar	12; 20; 9	75	163 (15)	298	12.1

2.4. Conversion to space mean speed

Since the observed speeds were instantaneous, their mean is a time mean speed \bar{u}_t and their variance is time mean speed variance, s_t^2 . However, FFS is a space mean speed, \bar{u}_s , since FFS usage in HCM 2010 speed-flow curves are based on the continuity equation of traffic flow (Gerlough and Huber, 1975), namely,

$$q = k \times \bar{u}_s \quad (1)$$

or in HCM 2010 notation (HCM, 2010b)

$$v_p = D \times S \quad (2)$$

Time mean speeds and s_t^2 were converted to \bar{u}_s and s_s^2 using the relationships

$$\bar{u}_s = \bar{u}_t - s_t^2 / \bar{u}_t \quad (3)$$

and

$$s_s^2 = \bar{u}_s (\bar{u}_t - \bar{u}_s) \quad (4)$$

Table 2: Mean Free-Flow Speeds

Speed Zone	\bar{u}_t	S_t^2	\bar{u}_s	S_s^2
mi/h	mi/h	(mi/h) ²	mi/h	(mi/h) ²
20	21.7	10.4	21.3	8.5
20	22.8	10.3	22.3	11.2
20	22.3	9.5	21.9	8.8
25	28.8	17.9	28.2	16.9
25	26.8	10.7	26.4	10.6
25	28.1	25.7	27.1	27.1
30	31.1	11.8	30.8	9.2
30	33.3	10.4	32.9	13.2
30	34.0	11.3	33.7	10.1
35	35.9	8.0	35.6	10.7
35	35.2	11.6	34.9	10.5
35	36.2	8.5	36.0	7.2
40	40.4	12.8	40.1	12.0
40	35.3	22.5	34.7	20.8
40	36.9	16.3	36.4	18.2
45	45.1	29.7	44.5	26.7
45	45.8	14.5	45.5	13.6
45	46.7	31.3	46.0	32.2
50	47.8	27.9	47.2	28.3
50	48.4	23.9	47.9	24.0
50	48.5	14.0	48.2	14.5
60	61.1	13.0	60.9	12.2
60	61.7	17.9	61.4	18.4
60	60.9	12.3	60.7	12.1
65	67.4	9.7	67.3	6.7
65	63.2	14.3	63.0	12.6
65	67.3	19.7	67.0	20.1
75	72.1	24.8	71.8	24.6
75	76.9	16.9	76.7	16.8
75	76.6	8.7	76.5	8.7

2.5. Site descriptions

The best way to describe the ten sites is to show a photograph of each one, Figure 1 through Figure 10. The team noted all speed observations at midblock points or points in pipe segments outside the influence of intersections, ramp operations, and weaving operations (Currin, 2001), (Homburger, 1996), (Robertson, 1994). For all sites, the two-member team used a Doppler device and tallied vehicles so that they were inconspicuous from the observed traffic. In other words, most anonymous drivers did not have sufficient time to react to the speed and volume study. It is important to note that posted speed limit signs reflect prevailing conditions. For example, a road crew signed

the sanctioned 60 mi/h (95 km/h) site at 60 mi/h (95 km/h) partially because of the horizontal curve on the site's pipe segment and nearby access points as shown in Figure 8.



Figure 1: 20 mi/h (30 km/h) Main Street Downtown Rapid City, South Dakota taken 9/24/2010.



Figure 2: 25 mi/h (40 km/h) South Elm Avenue Rapid City, South Dakota taken 4/11/2010.



Figure 3: 30 mi/h (50 km/h) South 5th Street Rapid City, South Dakota taken 4/11/2010.



Figure 4: 35 mi/h (55 km/h) Saint Joseph Street Rapid City, South Dakota taken 4/11/2010.



Figure 5: 40 mi/h (65 km/h) Hwy 44, West Omaha Street Rapid City, South Dakota taken 9/24/2010.



Figure 6: 45 mi/h (70 km/h) South Hwy 79 Rapid City, South Dakota taken 4/11/2010.



Figure 7: 50 mi/h (80 km/h) W. Chicago Street Rapid City, South Dakota taken 4/11/2010.



Figure 8: 60 mi/h (95 km/h) Hwy 16 Truck Bypass, Elk Vale Road Rapid City, South Dakota taken 4/11/2010.



Figure 9: 65 mi/h (105 km/h) Interstate 90, Exit 57 Rapid City, South Dakota taken 4/11/2010.



Figure 10: 75 mi/h (120 km/h) Interstate 90, Exit 48 South Dakota taken 4/11/2010.

3. Results

A scatter plot of FFS versus posted speed limit reveals a proportional linear relationship as shown in Figure 11. Subsequently, simple linear regression models revealed the strength of the association between FFS and posted speed limit both with an intercept term and without. One rejects the intercept term model from further evaluation because its adjusted R-square was slightly lower at 0.93 than the model with no intercept term at 0.99.

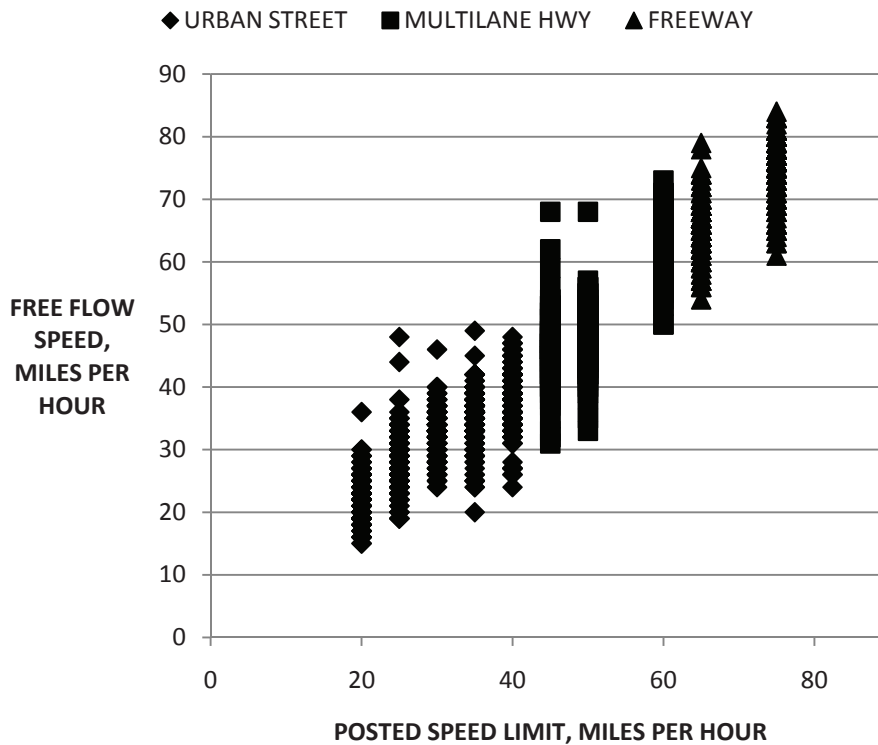


Figure 11: Free-Flow Speed versus Posted Speed Limit (N=1668)

The evaluation of the linear regression model without an intercept term reveals that the posted speed limit variable is significant at a level of significance at 5%; its P-value is 0.00%. The model

$$FFS = +1.01 \times (\text{Posted Speed Limit}) \quad (5)$$

is significant with a probability greater than F-value of 0.0000, i.e., at a level of significance 5%. Figure 12 shows the evaluation of the simple linear regression model. A very strong positive association exists between mean FFS and posted speed limit; the correlation coefficient is +0.99.

To determine if facility characteristics introduced any major differences in estimating FFS, simple linear regression analyses was performed by facility type, i.e., urban street, multilane highway, and freeway. With a sample size of 876 speed observations from five urban street sites, a correlation coefficient of +0.99 existed between FFS and posted speed limit. The urban street model

$$FFS = +1.01 \times (\text{Posted Speed Limit}) \quad (6)$$

is significant at 5% with a P-value of 0.00%. The three multilane highway sites with 474 speed observations resulted in the model

$$FFS = +1.00 \times (\text{Posted Speed Limit}) \quad (7)$$

in which the P-value was 0.00% and the correlation coefficient was +1.00. For the two freeway sites where the team made 318 speed observations, linear regression analysis produced the model

$$FFS = +1.01 \times (\text{Posted Speed Limit}) \quad (8)$$

whose correlation coefficient was +1.00 and P-value was 0.00%.

Model: MODEL1

NOTE: No intercept in model. R-square is redefined.

Dependent Variable: FFS FREE FLOW SPEED IN MILES PER HOUR

Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Value	Prob>F
Model	1	3762584.9802	3762584.9802	179185.967	0.0000
Error	1667	35004.01984	20.99821		
U Total	1668	3797589.0000			
Root MSE		4.58238	R-square	0.9908	
Dep Mean		44.58453	Adj R-sq	0.9908	
C.V.		10.27796			
Parameter Estimates					
Variable	DF	Parameter Estimate	Standard Error	T for H0: Parameter=0	Prob > T
PSD	1	1.008933	0.00238347	423.304	0.0000
Variable	DF	Variable Label			
PSD	1	POSTED SPEED LIMIT IN MILES PER HOUR			

Figure 12: Free-Flow Speed Model without Intercept (N=1668).

Simple linear regression models are valid only when the models meet the three Gauss-Markov assumptions. One assumption is that the observed free-flow speeds have a Gaussian distribution by site. The second assumption states that observed free-flow speeds are independent of each other. The third assumption requires that the plot of residuals versus observed posted speed limits reveals homoscedasticity.

For the first assumption, the team conducted a chi-square goodness-of-fit test for each site to determine if observed speed distributions followed a Gaussian distribution. The team cumulated data gathered at each site into an observed distribution by classifying speeds into increments of 2 mi/h starting with the lowest even recorded speed and ending with the classification that included the highest recorded speed. The fit of the distribution was checked using the Chi-square goodness-of-fit test at levels of significance of 10%, 5% and 2.5%. The chi-square goodness-of-fit tests revealed that one rejects at 5% the hypothesis that the Gaussian distribution does not fit the observed speed distribution in six of the ten sites. Table 3 shows the goodness-of-fit test results by site.

To ensure that observed speeds were independent of each other, the team inconspicuously measured speeds at flow rates less than 1000 pc/h. Table 1 shows flow rates at which the team measured speeds. All sites had flow rates less than 500 veh/h, and their traffic had average headways of more than seven seconds. Measuring at low flow rates ensure that preceding vehicle speeds do not affect speeds of following vehicles.

The plot of residuals versus observed posted speed limits reveals homoscedasticity. Figure 13 shows the plot.

Table 3: Summary Results of Chi-Square Goodness-of-Fit Tests

Speed, mi/h	χ^2 calculated	χ^2 theoretical			Reject at 5%
		$\alpha = 0.10$	$\alpha = 0.05$	$\alpha = 0.025$	
20	10.41	7.78	9.49	11.14	yes
25	8.93	10.64	12.59	14.45	no
30	1.55	7.78	9.49	11.14	no
35	15.94	6.25	7.81	9.35	yes
40	16.38	12.02	14.07	16.01	yes
45	11.94	12.02	14.07	16.01	no
50	8.70	12.02	14.07	16.01	no
60	7.09	9.24	11.07	12.83	no
65	5.77	9.24	11.07	12.83	no
75	40.00	10.64	12.59	14.45	yes

Legend: 1 = URBAN STREET, 2 = MULTILANE HIGHWAY, 3 = FREEWAY

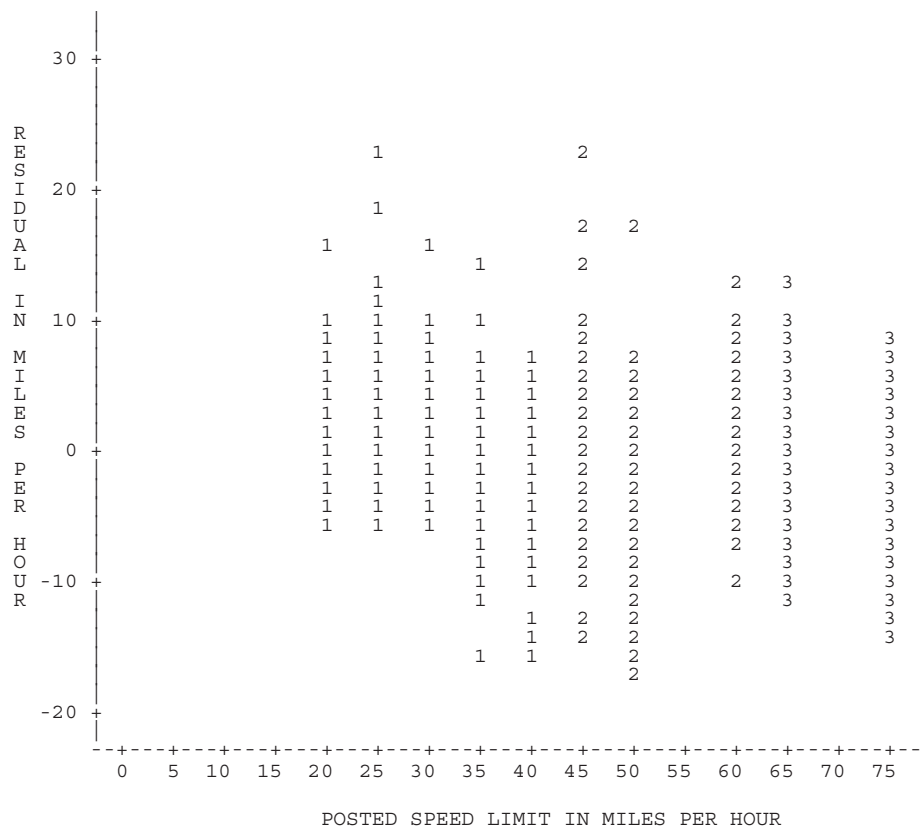


Figure 13: Residuals versus Posted Speed Limits.

4. Conclusion

The simplest model has a very strong positive association between mean free-flow speed and posted speed limit; the correlation coefficient is +0.99. Generally, the model meets the three Gauss-Markov assumptions. The model has two major limitations. Posted speed limits beyond the model's 20 mi/h (30 km/h) to 75 mi/h (120 km/h) range are extrapolations. The team collected speed data only in South Dakota. Driver behavior in other locations may be very different. Using the model to estimate free-flow speeds in other locations are extrapolations.

The results affirm previous research in that highway type has significant influence on operating speeds as shown in Figure 11; freeway traffic has higher average speeds than multilane highways and urban streets under base conditions. Within each highway type, average FFS had a strong association to the posted speed limit, i.e., +0.99, +1.00, +1.00 for urban streets, multilane highways, and freeways, respectively.

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